

Synthetic Vision Systems

Technical Report submitted to

**Crew/ Vehicle Integration Branch
NASA Langley Research Center
Hampton, VA**

Prepared by

Cambridge Research Associates, Inc.
1430 Spring Hill Road, Suite 200
McLean, VA 22102

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EXECUTIVE SUMMARY

More than 9,000 deaths have resulted from Controlled Flight into Terrain accidents since the beginning of commercial jet operations. Due to recent, high profile accidents, the search for a solution to the Controlled Flight into Terrain problem has been intensified. This report discusses one such solution, the introduction of a Synthetic Vision System into the cockpit.

A Synthetic Vision System would be comprised of high accuracy navigation information, a real-time in-flight database(s), a processing and rendering unit, flight parameters, and a display device. By identifying the precise, actual location of the aircraft within the in-flight database, a highly accurate depiction of the aircraft's surrounding environment and pathway can be provided to the pilot in a 3-D perspective view on an in-cockpit display.

However, in order to implement the optimum Synthetic Vision System, database, display, and liability issues must be resolved. This report addresses each of these issues in detail. Examples of particular issues are as follows:

- Database - Availability of Data
 - Requirements of a World-Wide Database
 - The Size and Storage of the Databases
 - Resolutions Requirements
 - Validation of Data
- Display - Display of Alerts
 - Spatial Cues
 - Display Devices
- Liability - Vendors
 - Users
 - Multiple Jurisdictions

In conclusion, this report makes a clear and concise stand for Synthetic Vision Systems as the solution to the Controlled Flight into Terrain problem. Although there are issues that must be addressed, it is apparent that the technology exists to the degree necessary to make this solution a reality.

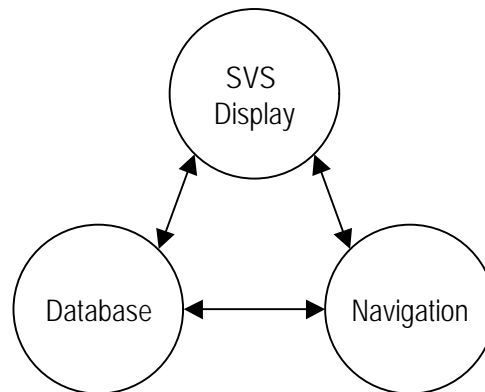
KEY WORDS: CFIT, synthetic vision, cockpit display, advanced terrain awareness, terrain symbology, aviation safety, automation, Flight control, Guidance system

1.0 INTRODUCTION

Controlled Flight into Terrain (CFIT) is a major cause of civil transport accidents, as recently evidenced by the crash of a 757 near Cali, Columbia in December 1995 and the crash of a 737 near Sarajevo in April 1996. Since the beginning of commercial jet operations, more than 9,000 deaths have resulted because of airplanes inadvertently flying into terrain, water or an obstacle. Many of these accidents involved hitting mountainous terrain, but more often the airplane crashed into relatively flat ground somewhere other than the intended landing site. In many of these crashes, the airplane was functioning properly (no airframe icing, wind shear, collision with other aircraft, or loss of control), but the ground was not visible due to clouds or darkness.

As a result of these accidents, domestic air carriers are now equipped with Ground Proximity Warning Systems (GPWS) (see details on the Enhanced GPWS in Section 4.0 below) that provide alerts to the pilots if they fly toward terrain. However, it is believed that advanced displays may augment safety by providing corroborating information about a terrain alert. Several projects have investigated issues related to advanced terrain awareness and alerting displays for civil transport cockpits (e.g. Kuchar and Hansman, 1993a) and several studies have examined the issues (such as database requirements, effectiveness of terrain symbology, and comparisons of plan view contour, side profile view, and three-dimensional perspective views of terrain) of bringing these displays into the cockpit.

It has been determined that a synthetic vision system (SVS) relies on the operations of a number of subsystems: high accuracy navigation, real-time in-flight database, processing and rendering unit, an interface to flight parameters provided by the aircraft and a display device with raster graphics capabilities. (Fig. 1 shows key elements of a synthetic vision system.) The aircraft's position is available with high accuracy and reliability using new navigation systems that combine GNSS and aircraft sensors. The precise positioning information can be employed, in conjunction with up-to-date databases, to provide the pilot with a three dimensional (3-D) perspective view of the aircraft's surrounding environment and pathway. These 3-D displays can restore the visual cues that a pilot is lacking during Instrumental Meteorological Conditions (IMC). Such a synthetic vision system is an effective way to enhance the pilot's situation awareness and to prevent CFIT accidents.



Synthetic Vision Key Elements

FIG. 1. KEY ELEMENTS OF A SYNTHETIC VISION SYSTEM

This technical report documents candidate requirement definitions for short-term, tactical needs as well as longer-term, strategic planning needs. Specifically, the report assesses synthetic vision requirements in terms of database, display and liability issues.

2.0 SPATIAL SITUATIONAL AWARENESS

Good spatial situational awareness is necessary to support the pilot's decision making process. A synthetic vision display, like flight deck windows, provides the pilot with tactical information about his environment to determine what he should do next. The synthetic vision system should provide information that supports guidance and control of the aircraft in its immediate environment (Abbott, 1993). This includes providing information that supports situation monitoring, situation assessment, decision making, and the execution of these decisions in the real-time spatial environment.

There are at least four elements that would constitute spatial situational awareness. First, it is necessary to know the relative location of objects within the environment. This includes position of our own aircraft (including attitude), location of terrain and man-made obstacles on the ground, the position of other aircraft, and the identification of necessary reference points (e.g., the airport or other useful landmarks). The location of atmospheric conditions such as clear air turbulence, microburst and thunderstorms would also be included in this category, as they can be considered to be obstacles that need to be avoided.

Second, it is necessary to know how the position of an aircraft will change over time with respect to other objects in the environment. For example, pilots would like to know if they are on a collision course with anything in the environment and how much time remains before impact given no modification of route.

Third, pilots need to know where in space their aircraft needs to be at different points in the future. This requires knowledge of an envelope in space that defines an acceptable range of positions. This envelope may be more or less well-defined depending on the situation and how far into the future pilots are looking. Knowing an aircraft's present and predicted position along with its desired position provides the error signal that guides control inputs.

A fourth requirement is knowledge of the spatial performance parameters of the aircraft (e.g., its maneuverability and ability to change speed). This information allows us to scale distances in terms of our ability to position the aircraft. There are two aspects of an aircraft's performance parameters that are desirable for a crew to understand. One is the desirable performance range based on considerations such as passenger comfort, company policy and regulations; the other, employed only rarely in an emergency, involves knowledge of the aircraft's outermost performance envelope.

3.0 TECHNOLOGICAL APPROACH

Synthetic vision provides pilots with a perspective out-the-window type of scene. Perspective displays of this type are highly intuitive, being close to our natural mode of spatial information gathering. They provide advantages such as the minimization of training and the ability to quickly process large amounts of information. An ideal synthetic vision system involves effective utilization of computer generated perspective images, real-time imaging sensors and efficient fusion of data derived from disparate sources. Fig. 2 illustrates

various components of a synthetic vision system, and a general approach to the creation of three-dimensional, real-time visualization of the terrain and elements of spatial situational awareness.

Perspective image displays are generated from an on-board database containing digital terrain, image and object data as well as man-made terrain features (such as buildings, towers etc.). These computer-generated images should be augmented with real time sensor information to depict transient events such as another aircraft encroaching on the active runway, as well as real-time weather data. Because of the great design flexibility, perspective images can display a wide range of information in a variety of ways to meet specific perceptual and information needs of the pilots.

4.0 EXISTING SYSTEMS

To date, several terrain alerting systems have been developed, some of which are being installed in a number of aircraft. The following paragraphs briefly review design and capabilities of such existing systems. It is apparent that none of the systems has the real-time 3-D terrain generation and display required for a SVS.

The Enhanced Ground Proximity Warning System (EGPWS), developed by AlliedSignal Aerospace, is an improvement over the traditional GPWS. The EGPWS provides the flight crew a map-like display of nearby terrain and sounds an audible alert at approximately a minute's flight time or more away from terrain. Traditional GPWS sounds a warning from a few to approximately 30 seconds away from terrain, but averages 10 to 15 seconds. This system utilizes a grid based worldwide terrain database produced using terrain information provided by several countries. The EGPWS is linked to the airplane's navigation system to obtain aircraft location and is, therefore, referencing to the appropriate part of the terrain database. Using the aircraft's altimeter, the system computes aircraft's height and determines which terrain is high enough to represent a threat. Lufthansa German Airlines is installing the EGPWS on its entire fleet.

Terrain from 2,000 feet below the aircraft's altitude and higher are shown on the airplane's weather radar display or electronic flight instrument system. It appears as a *bird's-eye view* or map-type presentation using different colors and densities of dots. If the system issues an audible alert, the terrain that poses a threat is shown as a solid block of yellow or red, depending on the severity of the condition. The system constantly searches the data base along the aircraft's projected flight path, giving the system a virtual look-ahead capability. If the system determines the aircraft's flight path would take it too close to terrain in the database, it sounds the audible alert. This sound comes even earlier than a minute if the terrain is particularly high above the airplane's altitude.

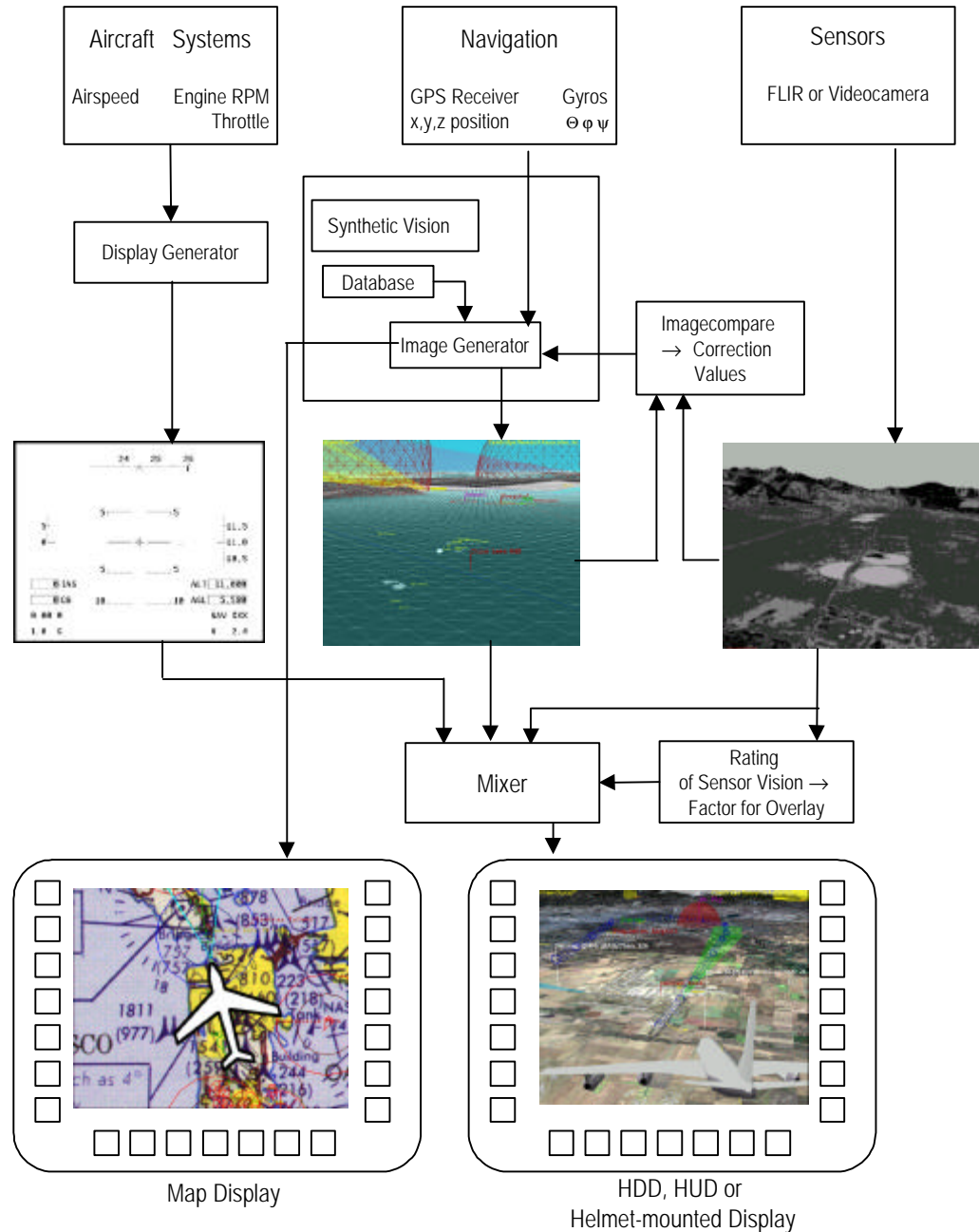


FIG. 2. COMPONENTS OF A SYNTHETIC VISION SYSTEM AND A GENERAL APPROACH TO REAL-TIME THREE-DIMENSIONAL VISUALIZATION OF TERRAIN AND SPATIAL SITUATIONAL AWARENESS ELEMENTS.

NASA Ames Research Center and the Georgia Institute of Technology are developing a prototype primary flight display format designed to re-enforce the pilot's model of both lateral and vertical navigation in near-terrain situations. Specific emphasis has been placed on the terminal phase of flight with terrain modeling in the vicinity of the departing and destination airport. The design incorporated perspective symbology that depicts the aircraft's

predicted position and terrain clearance information for up to 75 seconds ahead of the aircraft. The projection of the flight path is based on a *fast time* modeling technique. This technique utilizes roll stabilized vertical color-coded lines, *whiskers*, positioned at 15-second intervals out to 75 seconds. The display also incorporated a dynamically color-coded terrain grid. Man-made obstructions, such as radio towers, are also shown on the terrain grid. Information for building the terrain and obstruction files is obtained from the approach plates for each runway in the scenario.

An experimental evaluation of the display is being conducted on-site at Delta airlines. Each test pilot will fly three scenarios based on actual controlled flight into or toward terrain using one of three displays: the baseline cockpit display, the primary flight display, and the NASA Ames / Georgia Tech display with flight path predictor and ground terrain information. Attention diverting tasks are implemented, and Air Traffic Control (ATC) communications are also using simple voice communications without supporting electronic intercoms. The goal of the experiment is to measure how quickly pilots can detect dangerous terrain with each of the three different display formats.

5.0 DATABASE REQUIREMENTS

Highly accurate terrain, obstruction, noise abatement, and airport database are required to implement synthetic vision concepts for CFIT and runway incursion reduction. Developing and implementing a worldwide, standardized database is essential for global implementation of synthetic vision systems and has been proposed by a number of recent studies (e.g., Moller and Sachs, 1994; Schiefele et al., 1997; May et al., 1998). The first step in doing implementing this database would be to combine the different data sources and different data types into a worldwide global database. Then, the Real-time Onboard database (RTO-DB) is derived from this global database (Fig. 3). The following sections describe various SVS database requirements, including data availability, worldwide database requirements, size / storage requirements, resolution requirements, database organization, real-time onboard format, database configuration control, and real-time validation.

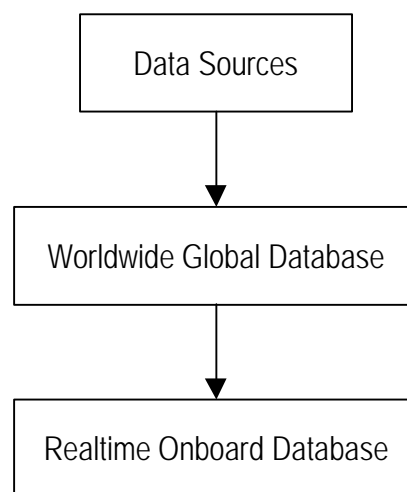


FIG. 3. SCHEMATIC DIAGRAM OF A GLOBAL DATABASE SYSTEM FOR THE IMPLEMENTATION OF A WORLD WIDE SYNTHETIC VISION SYSTEM.

5.1 Data Availability

Existing data are available in many different formats and several coordinate systems. These disparate data need to be integrated into one coherent global database with no data redundancy. A large-scale database might be assembled at moderate cost by using as much pre-existing data as would apply; however, much of this data might not be of sufficient resolution to support the *elevation-data-only* (no imagery) approach suggested. In particular, 15 m U. S. Geological Survey (USGS) data, which is essentially free of charge except for media and handling costs, probably has neither the required resolution nor accuracy. The following paragraphs highlight details, including sources, resolution, and update frequency, of a number of data elements required in building a SVS.

5.1.1 Elevation Data

Digital elevation data are available for the entire world and also for a number of countries. Gittings (1997) presents an exhaustive list of available data with information on their source as well as explanation. Data are available for a number of countries including American, European, Asian and African nations. These data are in a number of different formats (VPF, DTED, binary raster, Arc/Info, ASCII, Intergraph DGN, ERDAS, DXF, etc.) and are of various resolutions. Horizontal data resolution varies from 30 m (e.g., Defense Mapping Agency's DTED data) to 1:1 M as well as 1 degree x 1 degree. Some of these data are available free of charge, while others are available for a fee starting at around \$100, with varying costs, depending on resolution and coverage. DTED data are available from the National Imagery and Mapping Agency (NIMA) in World Geographic System (WGS84) coordinate system (DMA, 1986). DTED level 1 elevation post spacing is 3 x 3 arc second (approx. 90 m), and for an Area of 1 degree x 1 degree the required storage is about 2.8 MB. DTED level 2 elevation post spacing is 1 x 1 arc second (approx. 30 m). DTED is a step towards generating a worldwide digital terrain database (90 South to 89 North, 180 west to 179 East). The absolute horizontal accuracy requirements for both Level 1 and Level 2 data are 130 m, C. E. 90% WGS84, while the absolute vertical accuracy requirement is ± 30 m L. E. 90% MSL.

For the contiguous United States, Hawaii and Puerto Rico, digital elevation model (DEM) data are available from the USGS (USGS, 1997). The USGS produces DEM in five primary types, including a 7.5-minute data (30 x 30 m data spacing cast on Universal Transverse Mercator (UTM) projection), and provides coverage in 7.5 x 7.5 minute data blocks.

Rectangular grids and triangular irregular network (TIN) are the two techniques used to represent digital elevation. Their simplicity and regularity characterize rectangular grids. TIN reduces the amount of data in the database without reducing accuracy and ensures rendering performance for SVS displays by reducing the number of polygons (Fig. 4). For a worldwide SVS, even the TIN data is too large to be drawn at an acceptable frame rate on today's graphics machines. Therefore, polygonal decimation should be used to reduce the number of triangles to be rendered. Most algorithms used for decimation (viz., clustering, data removal, topological imitation, texture maps) were developed for the visual quality of the decimated terrain. Parameters of these algorithms do not allow performing an error bounded decimation because they are based on criterion like *face angle* or *bounding box size*.

However, for an SVS, it is necessary to know the absolute error introduced by the decimation. May et al. (1998) developed an algorithm based on the *Data Removal* principle to eliminate vertices only if the newly introduced error is smaller than a given threshold. Using this algorithm, the study reports that, in general, up to 50-60% of the single points can be eliminated without introducing any significant error (i.e., error < 10 m) even in very mountainous areas. In addition, this algorithm attempts to preserve important terrain features such as ridgelines.

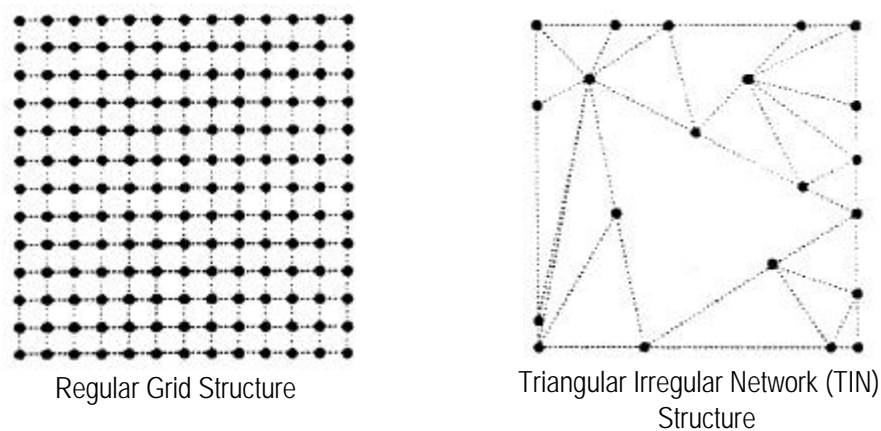


FIG. 4. REGULAR GRID AND TRIANGULATED IRREGULAR NETWORK STRUCTURE FOR REPRESENTING ELEVATION DATA.

5.1.2 Radar Elevation Data

The capability to acquire 3 m elevation data (with 2.5 m vertical accuracy) by means of Interferometric Synthetic-Aperture Radar for Elevations (IFSARE) has been developed by the Environmental Research Institute of Michigan (ERIM). This system uses interferometric radar techniques aboard a Model 36 Learjet to collect and record phase history data that are then ground processed into DEMs. IFSARE employs a Differential Global Positioning System (DGPS) to obtain accurately geo-coded, rectified data. Since it uses radar techniques, IFSARE data can be obtained in all weather, day/night, and through atmospheric obscurants. The sensor, however, cannot collect phase history data in areas where there is insufficient radar return, such as water bodies and slope-induced shadows. ERIM has collected data over the U.S. sector in Bosnia as well as the Sarajevo/Gorazda road corridor. The data is available from NIMA in a data format that meets DTED specifications. It is estimated that the cost of acquiring 3 m elevation ranges from \$12 / km² (for data already in hand) to perhaps \$100 / km² (for data requiring dedicated aircraft operations). Using the larger figure puts the cost of data for a 100-airport database at \$10 M (Mayse, 1998).

5.1.3 Image Data

The Earth's surface is routinely mapped by a variety of sensors mounted on a number of remote sensing satellites and airborne platforms. Remote sensors collect reflective and emitter responses from the Earth's surface features, and remotely sensed data are useful to accurately map the Earth's terrain features. Remotely sensed data are routinely collected at

specific wavelength bands covering the entire portion of the electromagnetic spectrum. However, imagery collected from sensors operating in the visible (0.4 - 0.7 μm wavelength) and near-infrared (0.7 - 1.1 μm wavelength) bands are useful for terrain simulation and visualization. These data are available in a number of spatial resolutions. For example, spatial resolution range from 5 m (e.g., Indian Remote Sensing data), 10 m (French SPOT satellite data), 30 m (Landsat Thematic Mapper data) to 80 m (Landsat MSS data). These image data are available from a number of different sources as described below.

Image data are available from NIMA in the Controlled Image Base (CIB) format at 5 m and 10 m resolutions and in WGS84 coordinate system. Other image data sources include ARC Digital Raster Imagery (ADRI) from the U.S. Air Force Intelligence Support Agency. The Digital Orthophoto Quadrangle (DOQ) data is available from the USGS at 5 m and 10 m resolutions and in UTM co-ordinates. Image data are also supplied in a variety of formats including GeoTIFF, TIFF, GIF, JPEG etc. The data sets often have high partial resolution (0.5 m and 1 m). High-resolution images demand more storage requirements. For example, a 5 m resolution image requires a storage of about 455 megabytes (MB) for an area of 1 degree x 1 degree at the Equator.

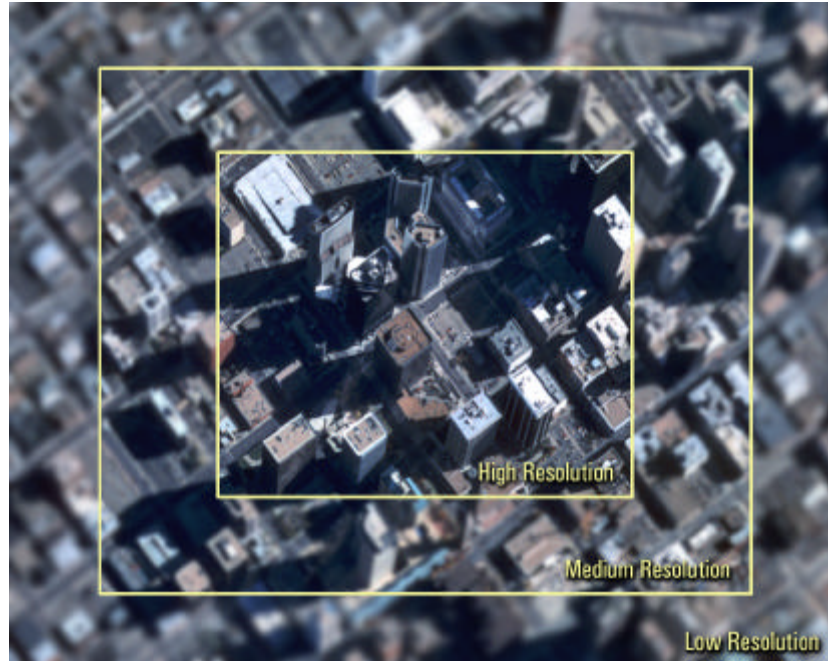
Images of different spatial resolutions can be accurately merged into each other to generate a mosaic for an area. Image integration techniques are a key feature of a SVS that enables accurate terrain visualization using both high-resolution images as well as recent or the most up to date information. This capability is especially important for airport proximity areas that have high fidelity database (see Section 5.1.5). Fig. 5 illustrates results of a multi-resolution image integration technique for both urban areas and airport runway approach.

5.1.4 Culture Data

Digital culture data include point features (single buildings, high-tension transmission towers, etc.), linear features (transmission lines, streets, roads, etc.) and areal features (cities, forests, etc). The geometry of linear and areal features is represented by polylines. In main memory, every coordinate point needs a total of 10 bytes (2 bytes for its elevation and 4 bytes for horizontal and 4 bytes for vertical coordinates).

Culture data exist in a variety of formats including Vector Product Format (VPF) and Digital Feature Analysis Data (DFAD) from the Department of Defense, and Arc/Info export format and ArcView ShapeFiles from ESRI. The structure and organization of the VPF format are based on a geo-relational data model suitable for large geographic databases. This standard format is mainly intended for direct use (DOD, 1996). The DFAD are derived from various planimetric, photogrammetric, and intelligence sources. This data are utilized to collect cultural features which, along with appropriate descriptive information, are converted into digital form for inclusion in a final culture file.

(a)



(b)

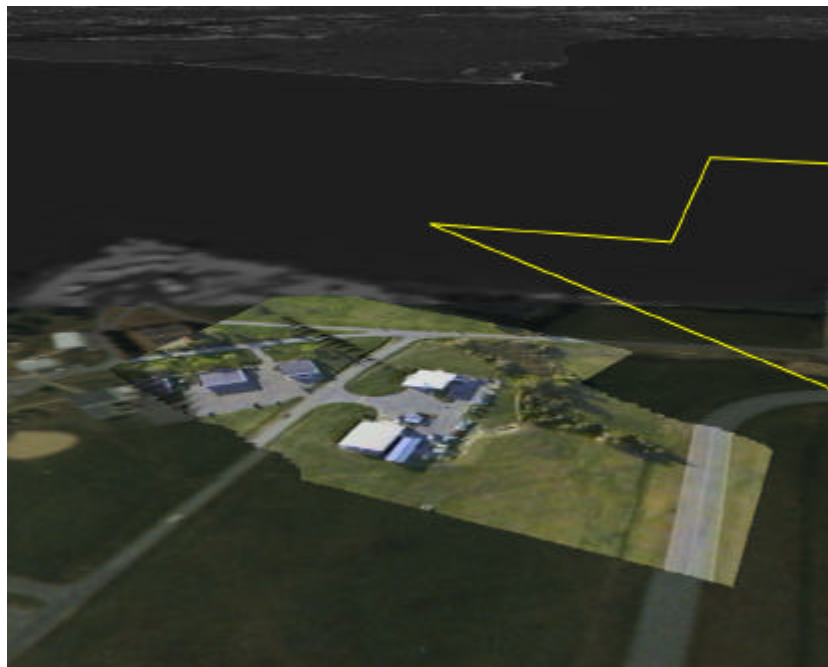


FIG. 5. ILLUSTRATION OF MULTI-RESOLUTION IMAGE INTEGRATION DURING 3-D TERRAIN VISUALIZATION. Data derived from different sensors and / or sources can be effectively merged with high geospatial accuracy. Input images can be extracted from an existing database, or high-resolution data can be received in real-time through a datalink. (a) Integration of low and medium resolution images with high-resolution ortho-photograph of Denver, Colorado; (b) Integration of a 0.5 m resolution image with a 1 m image that was acquired and visualized in real-time.

The DFAD data are available in Level 1 and Level 2. The absolute horizontal accuracy requirement for both Level 1 and Level 2 planimetric data is 130 m, C. E. 90% WGS. The relative (point-to-point) horizontal accuracy requirement for Level 2 planimetric data is 26 m, C. E. 90%. There is no relative (point-to-point) horizontal accuracy requirement for Level 1 DFAD. The heighting accuracy requirement for vertical obstructions which are 46 m or greater is ± 10 m (90% assurance above ground level). For obstructions less than 46 m high that cannot be measured within a ± 10 m heighting accuracy, a height of 24 m has been standardized. The minimum dimensions of a DFAD Level 1 data set are 5 minutes (latitude) x 5 minutes (longitude) whereas the maximum dimensions are 1 degree x 1 degree. For the Level 2 data, the minimum and maximum dimensions are 2 minutes x 2 minutes and 1 degree x 1 degree, respectively.

5.1.5 Airport Mapping Database

Existing airport mapping databases contain geographic information limited to the airport surface movement area (viz. area used for the take-off, landing, and taxiing of aircraft) and any non-movement area either contained within their periphery or within 1000 m of its periphery. A standard database update period is 28 days, and any data that is expected to change at a rate more the standard period will not be part of the airport database. Instead, these types of volatile data (e.g., FIS data, traffic data, and weather data) are assumed to be available via other means such as voice, data link, or sensor. A standardized airport mapping database is available to all airport users (i.e., to all aircraft). Young (1998) lists information requirements (viz. industry charting resolution, minimum data accuracy, published resolution and integrity class) of such a standardized mapping database for flight deck applications and also summarizes a wide variety of applications. [Note: Young (1998) is a draft document and information therein is yet to be fully compiled]. These applications include surveillance and conflict/runway incursion detection/alerting, route hold-short depiction and deviation detection/alerting that are useful to enhance situational awareness of pilots, air traffic controllers, aviation operations (airline, cargo and general aviation). In a SVS, this information can be effectively visualized on 3-D terrain displays. Further, a SVS could make use of a number of spatial database themes or layers (such as centerlines, runway/taxiway edges, painted markings, and obstructions) that would allow pilots to assimilate specific displayed information types with the out-the-window 3-D scene.

5.1.6 Three-dimensional Building and Obstacle Models

Three-dimensional building and obstacle models are readily available in a variety of formats including OpenFlight format (FLT) by MultiGen Inc., Inventor format (IV) by Silicon Graphics, Silicon Graphics binary (BIN) format, AutoCAD DXF format, and graphic object data format (SGO) by Silicon Graphics. The 3-D models have to be stored only once in the database and are scaled, rotated and translated to their coordinate position according to the current view frustum parameters. A special treatment is considered necessary for objects the identification of which is important for the control of the pilot. This concerns terminal areas such as airports for landing and taxiing on the ground.

The 3-D building and obstacle models have to be employed in conjunction with the airport mapping database. This enables creation of an almost realistic view of the airport

environment. Laboratory flight testing of airport landing and takeoff suggest that it is not required to display texture information (location of windows and doors, number of floors etc) on the buildings. Instead, for CFIT applications, it is important to visualize relative heights of buildings and obstacles (e.g., transmission towers). Fig. 6 illustrates integration of 3-D building models with a SVS visualization for Denver, Colorado. It is clear from this figure that building models superimposed on a multi-spectral imagery realistically simulates an actual flight path over Denver.

5.1.7 Real-time Airport Surveillance Data

Real-time airport surface surveillance data are available from Airport Surface Detection Equipment (ASDE-3) radar at several U.S. airports. These data are provided to an Airport Movement Area Safety System (AMASS) that can detect potential hazardous situations on the airport surface. This automated system provides ATC with alerts and warnings of changes to the mapping database. Radar surveillance data are available in the radar's polar coordinate system (range and azimuth) relative to the rotating radar antenna location. With the advent of ADS-B and TIS-B data link services, surveillance data will be available to non-ATC users (e.g., pilots) throughout all phases of flight (Young, 1998).

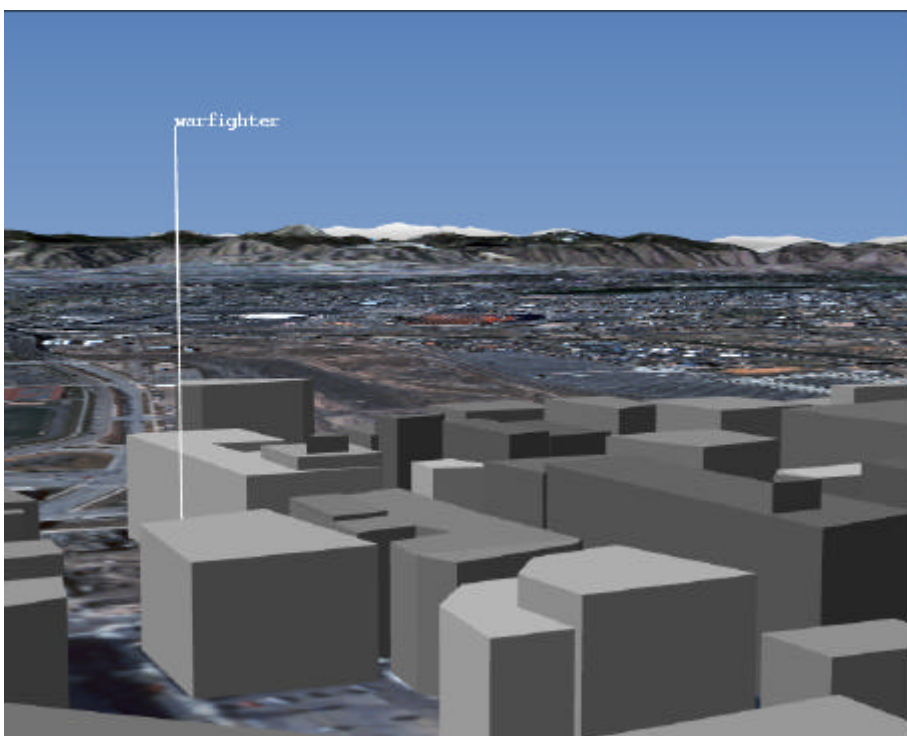
5.1.8 Real-time Sensor Data

5.1.8.1 Passive Millimeter Wave Sensor Images

Passive Millimeter Wave (PMMW) imaging sensors provide visual-like images of objects within their fields of view even under low visibility conditions (e.g., fog, clouds, snow, sandstorms, and smoke) that would blind visual and infrared (IR) sensors. Unlike synthetic images (i.e., computer generated), the PMMW image is real and completely passive, thus providing numerous advantages. A prototype sensor operates at 89 GHz frequency, and has a 30 degree x 15 degree field-of-view and a 0.5 degree angular resolution. The image update rate is 17 Hz, and the display rate is 30 Hz (Fornaca et al., 1998). Typically, PMMW sensors have been developed for Enhanced Vision Systems (EVS) to enhance pilots situational awareness, but yet to be flight tested (Ortiz, 1997; Tarleton et al., 1998).

PMMW sensor data suffer from certain shortcomings for effective use within an SVS. PMMW image resolution (i.e., sharpness) is diminished compared to visible and infrared images. Resolution improves with an increase in the sensor's optics. However, there is a limit to how much an aircraft can accommodate under its radome. Further, in an SVS display, PMMW data will have larger pixels for areas close to the sensor and the pixel size decreases with increasing distance from the sensor. In fact, this is exactly opposite of what is ideally desired in a SVS. Areas close to the sensor should be covered by smaller sized pixels, thus providing greater details of obstacles/ intruders. Image of far-away obstacle/ intruder could be rendered with coarse resolution pixels so that they are visualized with lesser detail.

(a)



(b)



FIG. 6. INTEGRATION AND VISUALIZATION OF 3-D BUILDING MODELS AND ANNOTATION LABELS IN AN SVS DISPLAY OF DENVER, COLORADO.
Building models are superimposed on multi-spectral satellite image for realistic terrain visualization. (a) A low altitude view close to a cluster of buildings; (b) A high altitude view of downtown Denver.

However, an SVS can effectively utilize PMMW data by extracting object / obstacle / intruder information from the raw PMMW image and then overlay extracted information on the visualized terrain. This involves a series of special image processing algorithms including spatial resolution enhancement, edge-preserving smoothing, template filter for runway symbology, Sobel/Hough for horizon detection, Kalman filter to provide a slow varying symbology and obstacle detection (see Fig. 7). This approach exploits the obstacle detection capability of a PMMW while overcoming the sensor limitations.

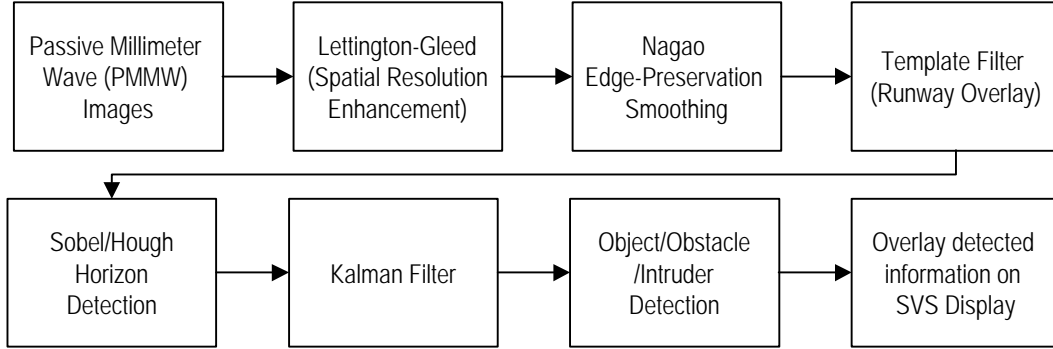


FIG. 7. IMAGE PROCESSING FLOW DIAGRAM FOR INFORMATION EXTRACTION FROM PASSIVE MILLIMETER WAVE SENSOR IMAGES.

Extracted information (runway boundaries, object outlines etc.) is then overlaid on an SVS display to visualize real-time positions of obstacles.

5.1.8.2 Thermal Infrared Sensor Images

Thermal infrared (TIR) sensing is an appropriate technology to identify, measure, and map changes in the surface temperature of objects. TIR sensors operate in 3 to 5 μm and 8 and 14 μm wavelength of the electromagnetic spectrum, and measure the radiant temperature of objects within their field of view. Therefore, TIR sensors are suited for nighttime application to delineate certain surface features (e.g. airport runways) and moving objects (e.g. aircraft and vehicles).

Thermal infrared images can be generated using a simulation procedure for training and flight test procedures. Fig. 8 illustrates the simulation algorithm, for which the input parameters include elevation, surface material classification, navigation data (current object information, aircraft location, time etc) and weather data as input parameters. Most of static input data are extracted from the RTO-DB, while the dynamic data are acquired through a real-time datalink. The infrared image output is supplied to SVS rendering engine for a real-time display. SVS will have capabilities to toggle the out-the-window visible scene with the simulated infrared image for precise and real-time recognition of features and objects. Fig. 9 shows a simulated 3-D view of thermal image for the China Lake region.

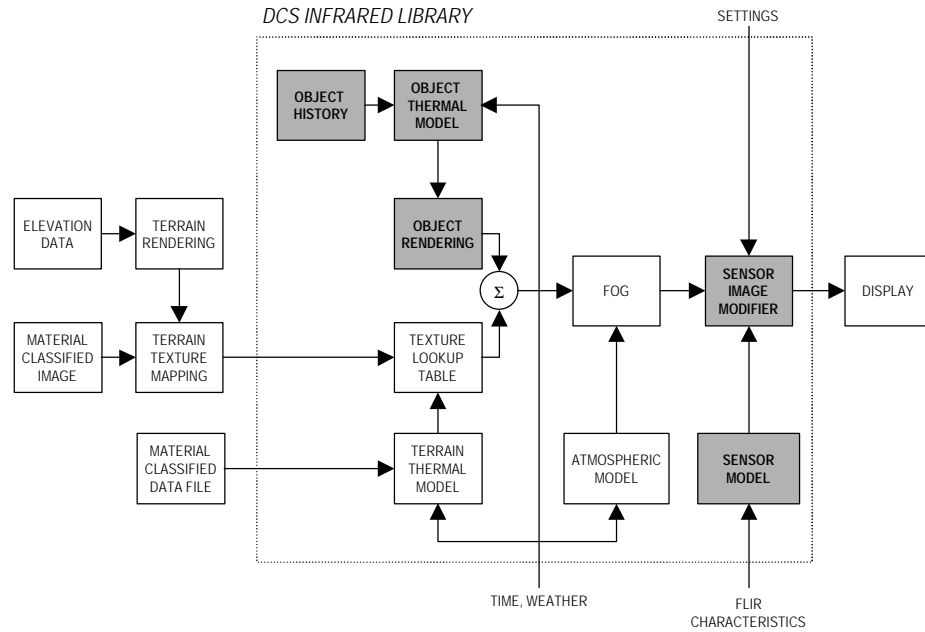


FIG. 8. GENERATION OF SIMULATED THERMAL INFRARED IMAGE DATA FOR SURFACE FEATURES AND MOVING OBJECTS.



FIG. 9. THREE-DIMENSIONAL VIEW OF A SIMULATED THERMAL INFRARED IMAGE OF CHINA LAKE REGION. White areas represent relatively hot surfaces and darker areas represent colder surfaces.

5.2 World-wide Database Requirements

For the worldwide application of a SVS, data elements described in the previous section have to be standardized on a global scale. Core elements of a global database include terrain (elevation and imagery), man-made obstacles, airport maps, special use airspace, and noise abatement databases. The worldwide database should have the following characteristics:

- (a) Standardized and very high consistency for data elements for the world coverage, and also for the displayed data. This will keep the pilots confidence in the system.
- (b) Uniform coordinate and projection system (e.g. World Geographic System, WGS84).
- (c) High quality data with acceptable vertical and horizontal resolution and accuracy.
- (d) Culture data and 3-D building and obstacle models for selected areas.
- (e) Capability for efficient integration and / or mosaicing of disparate data of various resolutions (for example merging of high resolution airport data with surrounding terrain information).
- (f) No redundancy between data elements and data layers. This will significantly minimize the amount of stored data.
- (g) Ability to monitor and estimate errors and data accuracy.
- (h) Functionality for relatively easy data update and query.
- (i) Implementation of a common graphical interface.

Technical requirements and standards for terrain, obstacle, and airport mapping databases in terms of vertical and horizontal accuracy, vertical and horizontal resolution and integrity are being defined by RTCA, Inc.'s Special Committee 193 and the European Organization of Civil Aviation Equipment (EUROCAE) Working Group 44. The requirements are being specified for all the phases of flight operation. These new standards will provide a public process *road-map* to ensure data base accuracy, resolution, and integrity, and other performance related parameters so that future databases are suitable for use in navigation. These standards will develop the necessary quality assurance provisions so those database elements can be employed in SVS, thereby promoting safety and thus encouraging speedy worldwide implementation.

It is expected that the global worldwide database would be quite large. As an example, an elevation database of only DTED level 1 data (3x3 seconds, approx. resolution: 90m) that covers the entire Earth would need storage space of approximately 100 gigabytes (GB). For imagery data made up of only CIB 5 m resolution data that covers the entire Earth's surface,

storage space of approximately 20,000 GB would be required. From this, it becomes obvious that adding higher resolution elevation, imagery, and culture data would greatly increase the size of the database.

In addition, the global database should be designed to allow for independent updates of elevation, imagery and culture data, and 3-D models. Due to the fact that elevation data rarely changes, this data would require few updates. Since culture data changes more frequently, it would require more updates. Also, the database would need to be updated to reflect any changes in local area data, such as new buildings at the airport, etc.

5.3 Size/ Storage Requirements

As working assumptions to support estimation, the following are suggested:

- (a) A basic terrain-avoidance capability can be provided using only high-resolution (e. g. 3 m) elevation data (without correlated imagery).
- (b) At many airfields in the Continental U. S. (CONUS), such as Kansas City, Indianapolis, and St. Louis, terrain-avoidance is not a significant problem, and data for such locales would not be required. A comprehensive initial capability could be achieved with coverage of 100 airfields.
- (c) On average, a terrain patch covering about 1000 km^2 would be required for each affected airfield. (This corresponds to a circle about 35.6 km in diameter, or a square about 31.8 km on a side).

Under these assumptions it appears that about 111,000 elevation posts could represent each patch. If each can be stored as a 32-bit (4-byte) integer, a single patch would occupy about 425 MB. The total storage required for 100 airfields would then be about 42 GB.

It is tempting to suggest that at the estimated size of 42 GB, the entire database could be carried aboard an aircraft. However, several considerations, as discussed below, argue against this assumption:

- (a) If current desktop-computer hardware could be used, the database would fit on around four high-capacity disk drives. The required enclosure might be about the size of a desktop system unit. Such space might not be readily available even in commercial-aircraft cockpits, and would be less so in general-aviation (GA) aircraft. The storage unit could be mounted elsewhere (other than the cockpit) in the aircraft, but this introduces a cable-run problem.
- (b) Even the foregoing premise - that desktop-type disk drives could be used - might be optimistic. Such units depend on high-resolution magnetic media for their capacity, which may not be compatible with on-board vibration and electromagnetic-interference (EMI) environments.
- (c) The calculations ignored at least two factors that would increase the size of a usable database. These are (i) inclusion of necessary *overhead* storage, e. g.

for file headers and directories, and (ii) provision for descriptions of ancillary non-terrain entities such as antennae and buildings.

With respect to these observations, and because the database would grow larger over time, a reasonable assumption is that data would be stored *off-board* and loaded into aircraft as needed to support operations. Commercial data warehouses already involve multiple terabytes of storage; even a 100 GB CFIT-avoidance databases would be comparatively modest. Setup costs and annual operating costs of such a facility should be on the order of \$5M or less.

5.4 Resolution Requirements

Experimental studies have suggested that pilots generally choose the highest available horizontal resolution, and prefer 500' or 1000' contour spacing intervals (Kuchar and Hansman, 1993b). Therefore, 500' and 1000' resolutions should be available to the flight crew. The mean response time for pilots to determine whether the flight route was clear of terrain was significantly lower when using the ownship-relative display as opposed to the MSL-relative display. However the pilot preferences favored the ownship-relative display over the MSL-relative display. The faster response times observed with the ownship-relative display indicates that this display may be more effective at providing pilots with an intuitive depiction of terrain hazards than the MSL-relative display, at least in straight, level flight situations. There was no significant increase in errors where test pilots misread the display as resolution was decreased. This implies that display reading error rates are not significantly correlated with the resolution levels selected by the test pilots, suggesting that limits on resolution levels will be set by mission requirements and not by human-factors issues.

5.5 Database Organization

Consistency is the most important requirement for the worldwide database. The WGS84 system should be used to achieve uniform consistency between various data elements. As noted earlier elevation, image data, culture data, and 3-D models are the most important data elements of a SVS system. Each element has its own data structure and is stored separately (Fig. 10) in the database. This organization enables easy update of one element when necessary.

Central to the creation of a robust worldwide SVS is the development of a universally consistent database, on which all other systems on the aircraft (for e.g., FMS, EGPWS and NAV-Displays) rely. This database named as High Quality Database (HQ-DB) eliminates redundancy and achieves necessary consistency at the same time. Such a central HQ-DB needs to be employed to generate a special application database for an aircraft's RTO-DB. This requires validation and integration of data from different sources and of different data types into one database to create a consistent HQ-DB. Creation of RTO-DB involves format adaptation and implementation of update strategies using a Database Server (DB-S). Fig. 11 illustrates the database creation process chain.

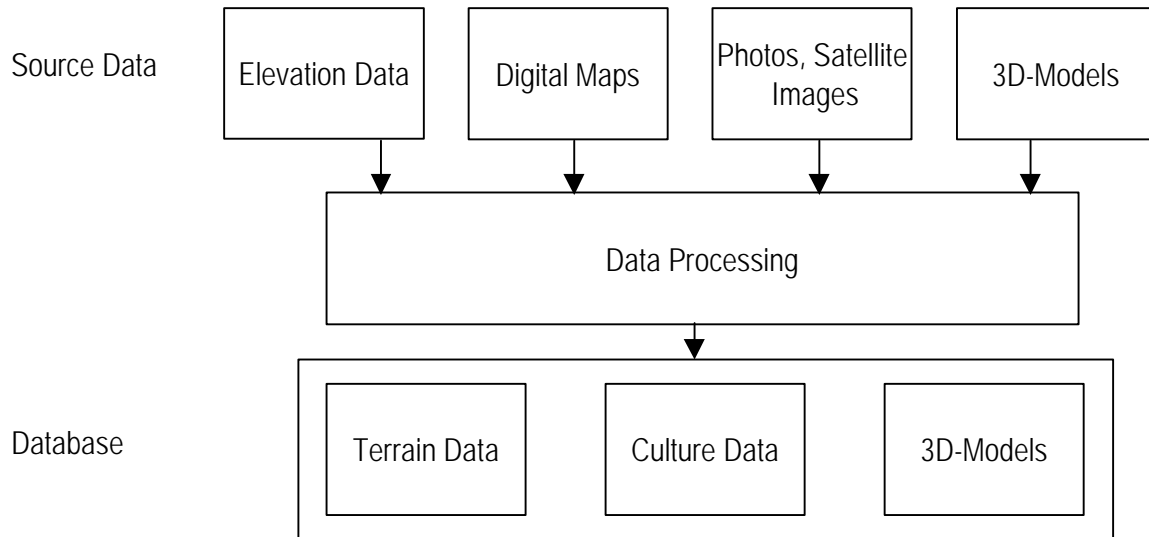


FIG. 10. ORGANIZATION OF DISPARATE DATA ELEMENTS INTO A WORLD-WIDE TERRAIN DATABASE.

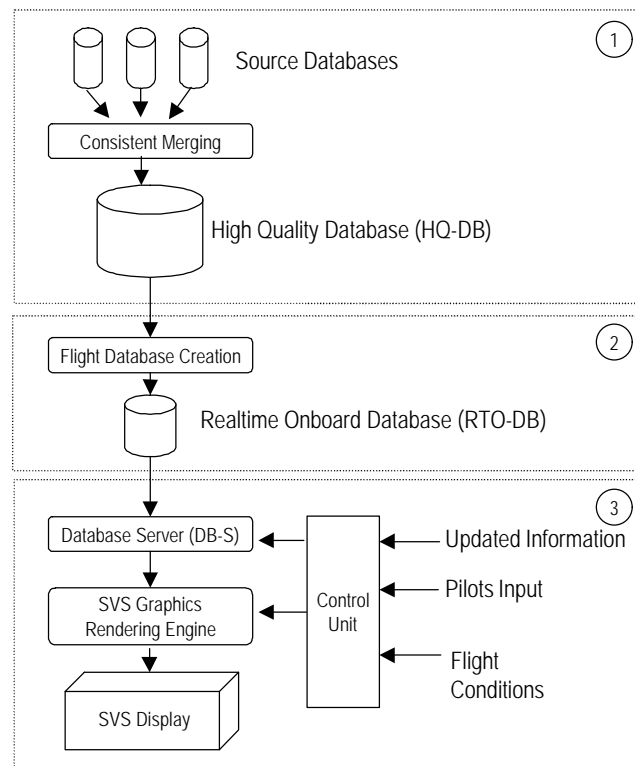


FIG. 11. SCHEMATIC DIAGRAM OF THE DATABASE CREATION PROCESS CHAIN.

As described earlier, source data are available from a number of sources, and have different formats, resolution, coordinate systems and quality (accuracy and error content). Therefore, it is necessary to integrate them into a single standard database based on a single format and consistent coordinate system. During the process of creating HQ-DB, data from different sources are downloaded and checked for consistency, transformed into a common geographic system (e.g. WGS84), and then integrated into a single database. A commercially available geographic information system (GIS) (for example, Arc/Info) is useful to solve data integration problems. GIS is an ideal system for handling both spatial data (both raster and vector formatted) as well as non-spatial data (Mattikalli et al., 1995). GIS tools facilitate conversion of all of the previously mentioned sources satisfactorily into a single GIS internal format. For different regions and applications it is necessary to store different data resolution and accuracy. Data that change rarely are directly integrated into the database. Real-time changes are performed by the DB-S.

The HQ-DB cannot be employed for real-time critical applications because the data extraction process is slow and storage memory in an aircraft is limited due to certification and pricing constraints. Also, high-end graphics rendering and visualization with an appropriate frame rate limits the quantity of information displayed to a pilot. Therefore, the database is transformed for a selected region into a real-time capable 3-D data format. Various GIS and image processing techniques, including Level of Detail (LOD), integration of synthetic and real features into the database and mosaicing, are to be applied as needed during the conversion process. The resulting RTO-DB can be stored on mass media such as CD-ROM and taken into an aircraft.

The graphics-rendering engine extracts data tiles required for the current mission region. The central control unit receives flight information such as position, heading, pilot inputs etc., data from sensors, and from a data-link, and then decides whether this information is processed by the DB-S or is directly supplied to the rendering engine. The rendering engine as well as the DB-S can handle cluttering / de-cluttering.

The elevation data can be organized in tiles, each tile representing a rectangular region of a predetermined size. Each tile is stored as a rectangular grid in the database. Image data can also be organized in a series of tiles. Data conversion is required since image data are available in a number of formats and varied coordinate systems. Culture data represents geospatial features such as roads, rivers, boundaries, etc. The geo-relational data model can be used to organize the culture data. Data from different sources need coordinate transformation and consistency needs to be ensured. Models representing objects such as buildings, obstacles, transmission towers, bridges etc., are stored in the database in 3-D object geometry format having a relational structure in order to store attribute information of geo-spatial features.

5.6 Real-time Onboard Data Format

For SV systems, real-time conversion processes are necessary due to the fact that most input data are not real-time capable concerning feature selection and conversion to 3-D models. The HQ-DB exported from the GIS cannot be directly utilized because of the topological information stored with the data and the resulting complexity of export filters. Geometrical representation and feature attributes are separated in different file formats, and also that GIS tools do not support functionality needed for real-time graphics application.

It is necessary to develop a data format that allows for:

- (a) real-time data storage;
- (b) arbitrary object extraction; and
- (c) storage of arbitrary feature specific attributes with each object.

Further, the real-time conversion process should include the benefits of 3-D graphics data formats to create a completely renderable scene. The following are characteristics of such a real-time data format:

- (a) single format for all data (an integrated concept);
- (b) tiling for different regions;
- (c) non-equidistant storage for terrain data (i.e., use of TIN);
- (d) storing of different LOD (levels of detail) within the data; and
- (e) arbitrary polygonal representation for objects.

A standard file format, such as Flight, Inventor, Medit, etc. accomplishes the above goals. Within this file format, a certain hierarchy and order of models are established to satisfy the above constraints.

Commercial tools such as Multigen are available for data conversion, but they are usable for manual supported conversion in small regions (about 50 x 50 km). For a large region typically used in a SVS, conversion needs to be performed without manual interference. Fig. 12 shows various steps performed during the HQ-DB to the RTO-DB conversion.

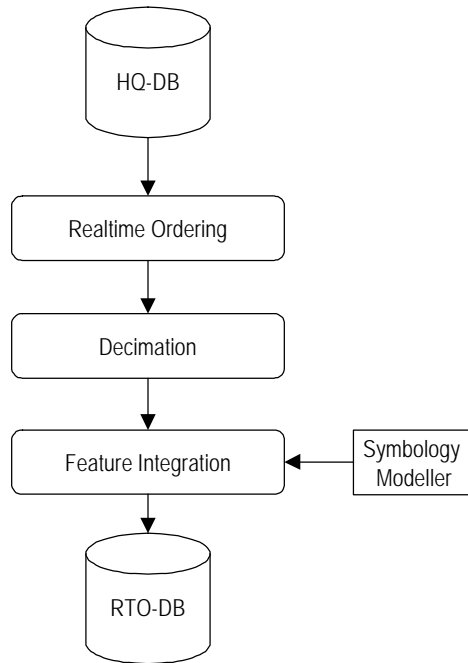


FIG. 12. DATA CONVERSION PROCESS FROM HIGH QUALITY DATABASE TO REAL-TIME ONBOARD DATABASE.

5.7 Database Server

The RTO-DB will be a static unchangeable database that serves all the information derived from the HQ-DB. But, there are certain pieces of information that cannot be incorporated in databases due to either the dynamic nature of the data (for e.g., real-time weather information) or the fact that the information changes since creation of the HQ-DB (for e.g., recent construction of buildings or towers). Such data are supplied by an online data-link, and the database server incorporates the updates before information is passed from RTO-DB to the SVS graphics-rendering engine (see Fig. 11). Besides the update task, the DB-S offers the ability to perform certain other tasks including data pre-selection and data caching functions. The DB-S would also scan the incoming data and supply appropriate geometry of features due to the fact that certain features from the database may have no geometric representation or some features have to be displayed with an alternate geometry.

A complex intelligent server is required for implementation of the DB-S. This server performs tasks of a simple server as well as more tasks that are interesting and more complex in nature. Trivial tasks of a simple server include receiving the data request, fetching the data, checking for pending updates, and supply the updated information to the SVS. In addition to these tasks, an intelligent server will have access not only to update information but also to data selection criteria and the necessary information to apply it to the selection process. This enables the pre-selection of data, data caching, and providing a geometric representation for database features. Most of these functions require a close interaction with the graphics-rendering engine. A control unit will be attached to DB-S to facilitate required interactions (Fig. 11). Specific tasks of the control system include coordination of information and data transfers between rendering engine, DB-S and superior aircraft control systems.

5.8 Database Configuration Control

The primary problem is to ensure that the CFIT- avoidance database accurately represents the real-world situation. Fortunately, the relevant aspects of the latter are fairly stable. The principal events affecting the layout of terrain, such as earthquakes and volcanic eruptions, occur infrequently and with ample publicity. If necessary, it should be possible to revise elevation maps for the (typically limited) affected areas in a matter of days. Moreover, construction of tall structures is a slow and well-documented process, providing sufficient time for developing the database modifications needed to reflect these. As the hazards to aviation posed by tall structures have long been known, it can be assumed that such construction projects already require notifying regulatory authorities.

It is also not difficult to represent structures such as buildings and antennae in formats suitable for visual presentation on cockpit displays. Such objects are typically of simple geometry, and are readily simulated using commercially available object-modeling software. It can be concluded that neither the problem of discovering the need to modify the database or of actually doing so, is technically formidable.

Before being placed into service, new data would be verified by flight tests under visual conditions. The test would be designed to check the accuracy of terrain and obstacle representations and the suitability of auxiliary displayed information such as approach-path cues. Flight crews could be confident that other aviators had approved data provided for their use.

Another concern remains regarding configuration control: If it proves advantageous to use multiple storage facilities, these should have a means of ensuring that they have consistent data. This problem is analogous to that of real-time validation, so the discussion in the next section should suffice for both.

5.9 Real-time Validation

At the end of the data stream is the most-frequent problem: Ensuring that the database loaded for a flight is the correct one, and is not corrupted during the loading process. Both of these can be accomplished using existing techniques. It has not been determined which such techniques would be best for the CFIT-database problem, but the following can be considered representative.

The on-board database required for a flight would comprise perhaps 500 MB. It would fit easily onto a compact disc (or even a digital audio- or videotape). The flight crew would load the database--probably before departure, but perhaps even en route. The loading software, which would reside in the on-board system unit, would load the database and then generate a verification message. This would include information (such as route and destination) from the flight plan; the data patch's identifying header; and the result of some verifying computation such as a checksum or cyclic-redundancy check.

The verification message would be sent (presumably by a wireless link) to a (or the) central facility, where it would be compared to stored reference information. A return message would advise the crew whether the load was successful. If not, but if time permitted, the crew might obtain another copy of the data—perhaps by direct broadcast, perhaps from a source at the airport. If verification could not be obtained but conditions were favorable, the flight could proceed using other pre-existing methods of CFIT avoidance.

Telecommunication costs change at rates that threaten to embarrass an estimate committed to paper. However, the communication problem nominally entails two transmissions per flight, each of no more than a few KB. Incidents of corruption requiring whole-database transmissions should be unusual, and require less than one GB each. Given a few tens of thousands of flights per day, the telecommunication costs for a comprehensive CFIT-avoidance system should not exceed those of many medium-sized companies.

A comprehensive data capability to support CFIT avoidance could probably be assembled for a fixed cost (data plus facilities) on the order of \$15M, with annual operating costs of \$ *a few* M, plus telecommunications costs. At least the latter would probably decline over time.

6.0 DISPLAY REQUIREMENTS

One of the key components of an SVS is the 3-D display of the out-the-window (OTW) scene. This involves the rendering of a number of display elements that constitute the scene as well as the display of a variety of spatial cues that simulate a real flight. Further, an SVS designed to reduce CFIT and runway incursions requires terrain-alerting displays to warn pilots when an aircraft's flight path intersects a minimum required altitude. Display systems (e. g. PowerScene) have already demonstrated the ability to present coherent scenes integrating multi-resolution data.

This section examines SVS display requirements in terms of terrain alerting displays, elements of spatial cues and OTW scenes.

6.1 Terrain Alerting Displays

Three advanced terrain alerting displays were studied in a laboratory part-task simulation to identify the best suited display method for different hazard situations, as well as the displays' abilities to convey the true level of hazard posed to the aircraft (Kuchar and Hansman, 1993b). The investigated displays were plan view depictions, profile views showing the vertical path of the aircraft relative to terrain, and three-dimensional perspective views of the terrain. The study concluded that no display format was entirely effective in conveying the true level of hazard when descending into flat terrain. In 50% of the cases where pilots used the plan or perspective views, the aircraft impacted the terrain before pulling out. The profile and perspective displays overemphasized the level of hazard when the aircraft was turning safely in front of a ridge line. Lateral maneuvers were initiated 80% of the time when using the plan view display, 30% of the time when using the perspective display, and in 5% of the cases with the profile display. Significantly fewer wings-level pull-up maneuvers were performed when using the plan view display as opposed to the perspective or profile displays. The study concluded that the plan or perspective displays were preferred because of the increased lateral information available on these displays.

6.2 Spatial Cues

Perceptual cues provide spatial information to an observer viewing a perspective scene. Of interest are those that will provide an observer viewing a two-dimensional perspective display an understanding of the three dimensional environment in which he or she

is operating. These cues to spatial perception can be divided into static and dynamic categories. An elaborate review of literature suggests that the quality and relevance of the existing studies vary greatly. Studies conducted to date encompass many different measures of subject performance, a wide variation in the quality of displays and varied subject skill levels. The following paragraphs highlight results of previous studies on spatial cues for cockpit displays.

6.2.1 Increased Scene Complexity

Increased scene complexity of a computer generated perspective display increases pilot performance. Pilot's estimate of altitude and aim point was superior when a runway was surrounded by farmlands with hills compared to fairly homogeneous flat surface or farmlands (Barfield et al., 1990). Similarly, approaches were found to be lower with reduced scene content or with narrower runways during an examination of the effects of variable scene content and familiar size cues on the performance of pilots flying landing approaches (Lintern and Walker, 1991). The speed and accuracy of detecting altitude changes improved with an increase in the density of vertical objects (Kleiss and Hubbard, 1993). Adding detail to individual objects to increase their realism produced no consistent improvement in performance. Texture mapping added to the terrain surface proved more effective than that when added to individual objects. Training and transfer of training were better with complex scenes involving river valley with buildings and 4000 ft. mountains on either side than with a scene having a white grid with a green background (Lintern et al., 1987). Vertical speed performance at landing was the best (2.45 ft/sec) for displays containing grid patterns with the more detailed grids (4 to 8 ft), next best performance was with the runway with standard markings followed by the bare runway (Buckland, 1980). However, Regal and Whittington (1993) found no difference in vertical touchdown velocity during approach, flare, and landing maneuvers using three different levels of cues: a plain runway, a runway with standard markings, and a runway with standard markings and general aviation aircraft parked to one side. But, the study reports that the pilots strongly disliked the plain runway as compared to the runways with standard markings.

6.2.2 Display Resolutions

Display resolutions do not significantly effect pilot touchdown performance but they tend to cause greater variability in flight path control during approach. Mann (1987) supported this argument in an examination of the effects of different resolution levels (400, 174, or 47 vertical lines) of millimeter wave (MMW) radar, and also identified a trend toward an increase in subjective workload with decreasing resolution.

6.2.3 Splay Angle and Texture Density

Wolpert et al. (1983) report that altitude loss was better detected when a descent took place over texture consisting of stripes parallel to the direction of travel than when the stripes were perpendicular to the direction of travel. However, there are contradictory studies that report poorest performance when flying over a parallel texture pattern and similar to one other pattern for the other two cases (Johnson et al., 1988; Johnson et al., 1989). Possible reasons

for these contradictions are the use of local optical elements such as display screen/ display element intersection location and angle in the Wolpert et al. (1983) study. Johnson et al. (1989) eliminated this potential artifact by including lateral wind disturbances that varied the aircraft's lateral position. Wolpert (1988) added disturbances in altitude and roll to test the possibility of local edge artifacts influencing performance, and confirmed the superiority of splay angle as cue for altitude regulation. Flach et al. (1989) also concur with this finding.

Optical flow rate (ground speed divided by altitude) appears to have an effect on perception of parallel and horizontal grid patterns. Flach et al. (1989) note that Johnson et al. (1988, 1989) used a lesser optical flow rate compared to other investigators. When a slower flow rate is used (although not as slow as that used by Johnson et al.), Flach et al. (1989) find that the superiority of the parallel line display was significantly less than that at higher rates. However, Kelly et al. (1993) report a superior performance for texture pattern parallel to the direction of flight and the grid pattern at four different flow rates in the presence of pseudo-random wind disturbances. The error rate for the horizontal grid did, however, decrease, as the flow rate became lower.

6.2.4 Motion Parallax

Terrain slope is perceived better when traveled parallel to it than when moving toward it or viewing a static display (Kaiser et al., 1990). The static scene and motion towards the slope tend to yield similar performance. This indicates that motion parallax has greater utility than differential optical expansion rates.

6.2.5 Frame Rate

Harris and Parrish (1992) tested the effects of four-image update rates (6, 11, 17, and 33 updates per second) on touchdown parameters including airspeed, sink rate, runway position and lateral runway position. The airspeed at touchdown was highest at the 6 frames per second update rate, and there was very little difference in the airspeed at touchdown for the 11-, 17-, and 33 frames per second update rate. The touchdown runway position increased with image update rate with no significant change in runway position for the 11-, 17-, and 13-frame rate. Authors reports the highest touchdown sink rate for the 6 frames per second and the lowest for the 17- and 33- frame rates. The touchdown lateral runway position was near the centerline with 6 frames per second and at the left of center for the faster update rates. The slower image update rate did not permit the pilots to perform a flare maneuver, while faster rates produced much better flare and touchdown performance. Subjectively, the study found that the pilots subjectively felt that the 6 frames per second update condition was jumpy. The 11 frames per second update condition seemed jumpy close to the ground. The two fastest update conditions (17- and 33- frames per second) were not noticeably jumpy for the maneuvers used in the tests.

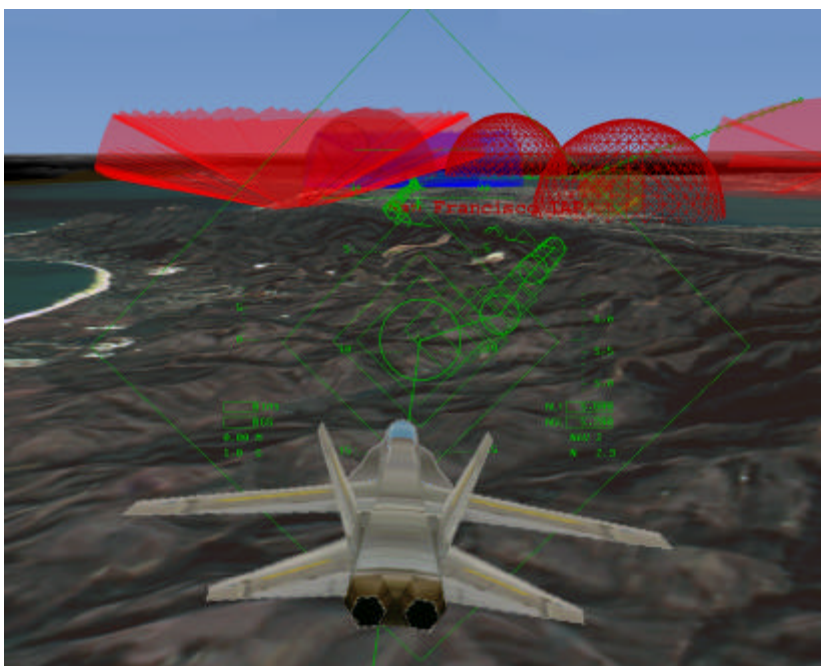
6.3 Out-the-Window (OTW) Scenes

A computer generated out-the-window (OTW) scene with overlaid heads-up-display (HUD) symbology shows significant promise for improving situation awareness, and this integrated pictorial formats can be the basis for an effective synthetic vision system. Parrish et

al. (1994) compared spatial awareness (own ship position relative to the desired flight route, the runway, and other traffic) of commercial airline pilots on simulated landing approaches using conventional flight displays with their awareness using advanced pictorial *pathway-in-the-sky* displays. In this simulated study, sixteen pilots repeatedly performed simulated complex microwave landing system (MLS) approaches to closely spaced parallel runways with an extremely short final segment. Four separate display configurations were utilized: a conventional primary flight and navigation display with raw guidance data and the Traffic Collision and Avoidance System (TCAS) II; the same conventional instruments with an active flight director; a 40 degree field-of-view (FOV), integrated, pictorial pathway format with TCAS II symbology; and a large-screen 70 degree FOV version of the pictorial display. The study used scenarios involving conflicting traffic situation assessments and recoveries from flight path offset conditions and showed that the integrated pictorial displays consistently provided substantially increased spatial awareness over conventional electronic flight information systems (EFIS) display formats. The study also reports that the wider FOV pictorial display gave equivalent objective results as the narrower pictorial format and subjectively was preferred by 14 of the 16 pilots.

Fig. 13 presents two OTW snapshots of a SVS flight approaching San Francisco airport. Fig. 14 illustrates spatial environment outside an aircraft as it approaches close to landing in Denver, Colorado (Fig. 14a) and the China Lake region (Fig. 14b). These illustrations were captured while flying simulated test routes. During the simulation, the planned routes are represented as highways-in-the-sky and rendered as a sequence of green diamonds. Waypoints of a route are indicated as circles on the route, and the actual flight line by a solid line. The HUD symbology is overlaid on the OTW scene and thus assists pilots in monitoring key navigation parameters including altitude, speed, etc. It can be observed from these figures that rendered image resolution changes according to the altitude of the flight. As the aircraft approaches the final landing phase, low-resolution images are replaced by high-resolution images, and 3-D building models, obstruction models and annotation labels start appearing in the scene. Aircraft ownship can be rendered in the OTW scene so that the relative position and altitude of other aircraft can be established and perceived.

(a)



(b)

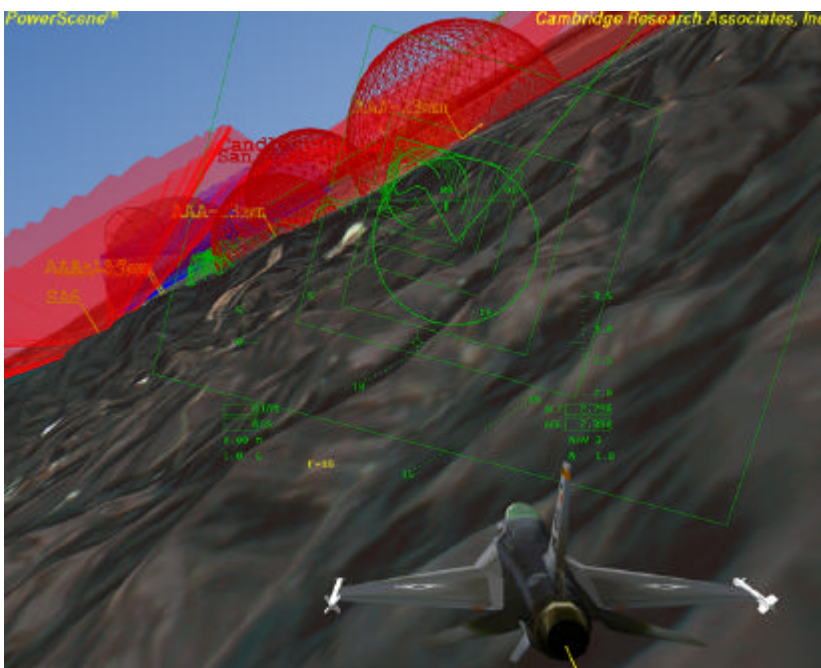


FIG. 13. SNAPSHOTS OF A SYNTHETIC VISION SYSTEM FLIGHT-PATH APPROACHING THE SAN FRANCISCO AIRPORT. The planned flight path is shown as a highway-in-the-sky and is displayed as a sequence of green diamonds and green circles on the path indicate waypoints. The figures also illustrate a scenario with several threat domes and dynamic emitters with their range and scanning pattern.

7.0 DISPLAY DEVICES

The computer generated 3-D OTW scenes must be displayed using a display device in the cockpit. All modern commercial jet transport aircrafts and many other older aircrafts are equipped with a weather radar display device, which could be used to display the OTW scene. Another approach would be to have a dedicated SVS display device in the cockpit. If this approach is selected, a number of issues, including retrofit into non-glass analog cockpits, display screen size requirement and advanced HUD capability, would then need to be addressed.

The Eagle-5 cockpit avionics display, introduced by DIPIX (a Xerox New Enterprise company) is a 5-inch by 5-inch high-resolution, active-matrix liquid crystal display (AMLCD) designed for U.S. Navy FA-18 Hornets, Marine Corps AV-8B Harriers and British Hawk trainers. The Eagle-5 is among the first AMLCDs that can display color tactical data, full-motion video and high-resolution monochromatic forward-looking infrared (FLIR) imagery from the same unit. The Eagle-5 incorporates a quad-green pixel pattern that offers higher resolution for monochrome FLIR imagery. The AMLCD design provides high brightness and contrast, saturated colors and reduced glare. It also eliminates *smearing* of full-motion video that plagues CRT and other military flat panel displays. The compact display is smaller, lighter, and requires less power to operate when compared with cathode ray tube (CRT) displays currently used in most fighter aircraft cockpits.

8.0 LIABILITY ISSUES

Effective implementation of a SVS demands a clear development of responsibilities among participating parties. It is evident from the previous sections that implementation of an SVS involves a number of data, hardware and software vendors, as well as different users with varied skill levels. A SVS must have clearly defined guidelines on the liability for all the vendors as well as the users. Liability issues become particularly important for worldwide application of a SVS and for flight over and / or connecting regions with different jurisdictions. In such cases, an international organization or consortium needs to act as a mediating and / or governing authority.

Before utilizing in an SVS, the databases should undergo strict verification and certification procedures from a recognized regulatory authority (such as the Federal Aviation Association (FAA)). The certification process should assess accuracy and validate all elements of the database. A standardized airport mapping database would allow implementation of clearly defined roles and responsibilities that eliminate procedural ambiguities that lead to operational errors and deviations.

The SVS graphics rendering engine must not introduce any new errors into the data. It is obvious that all raw data are associated with errors to some degree. Spatial errors are compounded through geo-processing, and therefore, there is a need to compute the accuracy of derived products. Further, the users must be provided with the error content and the precision of the data set so that the SVS can be utilized with a prior knowledge of confidence level.

The users (e.g. the pilots, flight planners, etc.) also have a responsibility to effectively utilize the SVS without any ambiguity and confusion with rendered OTW scene. The pilots have to utilize the SVS to make correct decisions during both tactical and strategic planning

and operation. More importantly, they need to practice or conduct strategic planning during a flight or when a flight is re-routed to a different destination. Further, a SVS should address liability issues concerning the unplanned flights (i.e., emergency landing after losing communication with ground control) as well as intrusive air traffic and objects.

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